BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024 B70 09085

SUBJECT: Physiological Limits on Skylab B Wobble During an Artificial Gravity Experiment - Case 620

DATE: September 30, 1970

FROM: R. J. Ravera

ABSTRACT

There are several recent studies concerning the wobble state and wobble control of the proposed Skylab B during an artificial gravity experiment. The wobble state is synonomous with the presence of angular acceleration and angular acceleration can produce adverse physiological effects in the crew. Therefore, physiological factors may set limits on the acceptable wobble state.

A method is presented which can be used to set wobble angle limits based on available data from ground based testing of angular acceleration perception thresholds. The numerical results presented are not considered absolute since the reliability and applicability of the data base is uncertain. They are considered conservative in the sense that tolerance thresholds are generally an order of magnitude, or more, higher than perception thresholds.

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MEMORANDUM FOR FILE

INTRODUCTION

When a spacecraft is spun to produce an artificial gravitational field, the rotational dynamics can cause physiological effects of a nature not experienced in ordinary Earth gravity.[1] These effects, which can influence man's gross and fine motor performance, may be present even if the rotating platform is perfectly steady. Steady rotation implies an angular velocity vector which is constant in magnitude and direction. If the rotation is non-steady, angular acceleration is present, and the spinning body is said to wobble. A wobble condition is then synonomous with the presence of angular acceleration, and creates additional stimulii which further distort the objective of producing a near natural gravitational field. A state of wobble can be produced by crew motions and/or undesirable torques or it may be the result of an off-nominal spin-up procedure. A commonly used measure of the wobble state is the wobble angle, defined as the angle between the angular velocity vector and the nominal body spin axis. The wobble angle is, in general, time dependent. G. M. Anderson[2] has proposed the use of a parameter called the excess energy ratio to characterize the wobble state, primarily because it enjoys the property of time invariance. In this work, results are presented in terms of both parameters, maximum wobble angle and excess energy ratio, for greater usefulness.

Determination of wobble angle limits is important to several studies being conducted of the artificial gravity experiment option for the proposed Skylab B. For example the effect of the spin-up procedure on wobble angle is important in assesing total control system requirements. A procedure is outlined in this memorandum which can be used to set acceptable limits using the results of ground based physiological testing of human subjects in spinning environments.

ANGULAR ACCELERATION SENSITIVITY

Since wobble is synonomous with angular acceleration, a logical starting point is to establish the ability of man to sense angular acceleration stimulii. The fluid motion in the semicircular canals of the inner ear are the means by which man detects angular accelerations about three approximately mutually perpendicular axes. The motion of the fluid is a measure of the angular acceleration stimulus and the brain reacts to the fluid motion by producing voluntary and involuntary reactions in the subject. The smallest magnitude of angular acceleration which can be sensed represents a sensitivity level or, in other words, a perception threshold. Two common physiological effects associated with a rotating environment, nystagmus blurring and Coriolis illusion, can be employed to establish perception thresholds. Certainly, using perception thresholds to set limits on wobble angle is the conservative approach since tolerance levels are generally much higher (by an order of magnitude, or more).

Nystagmus Blurring

Nystagmus blurring in subjects undergoing angular acceleration is caused by the involuntary slow drift of the eyes in one direction and the sudden rapid movement to an approximately central position. Because the effect is not subjective, it is a good indicator for the measurement of threshold. As reported by Larson,[1] an equation developed by Guedry and Richmond[3] that mathematically determines the threshold for nystagmus blurring is

$$6.8 \times 10^{-3} = \alpha(1 - e^{-0.1t}) \qquad (1)$$

where α is the threshold angular acceleration in rad/sec^2 and t is the duration of the disturbance acceleration in seconds. The number 6.8×10^{-3} is experimentally derived.

Coriolis Illusion

The name Coriolis illusion derives from the Coriolis acceleration term in the expression for particle acceleration in a rotating frame, $\underline{A}_c$, which is given by

$$\underline{A}_c = 2\underline{\omega} \times \underline{V} \tag{2}$$

where $\underline{\omega}$ is the angular velocity of the rotating frame and $\underline{V}$ is the velocity of the particle with respect to the rotating frame. When a subject positioned in a rotating frame as shown in Figure 1 nods his head with rate Ω, the relative velocity of any particle of the canal in the y-z plane at a distance r from the axis of head rotation (the y axis) is

$$\underline{V} = \Omega\hat{j} \times r\hat{k} = r\Omega\hat{i}$$

and the Coriolis acceleration of that particle is, from (2),

$$\underline{A}_c = 2\ \omega\hat{k} \times r\Omega\hat{i} = 2\ r\omega\Omega\hat{j} \tag{3}$$

Real forces will be transmitted by the structure of the body to provide these accelerations if the canal is to remain rigidly attatched to the head, which is assumed. Normal forces between the canal and the fluid within it will constrain the fluid so that it accelerates with the canal in normal directions. There are no similar tangential forces. Assuming an incompressible fluid, a relative tangential acceleration will exist between the fluid and the canal and it will appear to the subject, who is used to non-rotating environments, that he has an angular acceleration about the x-body axis. The tangential acceleration of the fluid in semicircular canal due to the Coriolis effect is the same as it would be with a real angular acceleration of magnitude

$$\alpha_x = \omega\Omega \tag{4}$$

Thus data on perception of the Coriolis illusion in a rotating environment is useful in determining perception threshold to real angular accelerations. A Coriolis threshold value used by Larson and reported originally by Clark and Hardy[4] is

$$\omega\Omega = 0.06 \text{ rad}^2/\text{sec}^2 \tag{5}$$

On investigation, it was discovered that this threshold is based on one subject only and, therefore, conclusions reached using this value should be so qualified. Another factor influencing the statistics is that some of the testing procedures require a subjective response by the individual. With these qualifications we can combine (4) and (5) and state that to be below the threshold of detection of the crewman, wobble angular acceleration must satisfy

$$\alpha \leq 0.06 \text{ rad/sec}^2 \tag{6}$$

It is important to note that the occurrence of the Coriolis illusion is in no way dependent on there being a wobble condition. That is, the Coriolis illusion can occur on a perfectly steady rotating platform.

The next step is to relate the values of α given in (1) and (6) to the wobble angle.

RELATIONSHIP BETWEEN WOBBLE ANGLE AND ANGULAR ACCELERATION

Let the x, y, and z axes be the axes of minimum, intermediate and maximum moments of inertia, respectively, of the Skylab B vehicle. Euler's equations for torque free motion of the spacecraft are

$$\left.\begin{aligned} I_x\dot{\omega}_x + (I_z - I_y)\omega_y\omega_z &= 0 \\ I_y\dot{\omega}_y + (I_x - I_z)\omega_z\omega_x &= 0 \\ \text{and} \qquad I_z\dot{\omega}_z + (I_y - I_x)\omega_x\omega_y &= 0 \end{aligned}\right\} \tag{7}$$

where ω_x, ω_y and ω_z are the components of angular velocity and I_x, I_y and I_z are the moments of inertias about the appropriately subscripted axes. As noted by Anderson(2), a good approximation to the wobble state is achieved by solving (7) with ω_z a constant, which gives

$$\left.\begin{aligned} \omega_x &= \omega_{xo} \cos \beta t - \sqrt{\frac{k_x}{k_y}}\, \omega_{yo} \sin \beta t \\ \text{and} \quad \omega_y &= \omega_{yo} \cos \beta t + \sqrt{\frac{k_y}{k_x}}\, \omega_{xo} \sin \beta t \end{aligned}\right\} \qquad (8)$$

where,

$$k_x = \frac{I_z - I_y}{I_x},$$

$$k_y = \frac{I_z - I_x}{I_y},$$

$$\beta = \sqrt{k_x k_y}\, \omega_z,$$

and ω_{xo} and ω_{yo} are initial values. The motion represented by (8) is that of $\underline{\omega}$ sweeping out a right elliptical cone around z. For a representative Skylab B vehicle,

$$k_x = 0.18,$$

$$k_y = 0.83,$$

$$\beta = 0.386\, \omega_z,$$

$$\sqrt{\frac{k_x}{k_y}} = 0.467$$

and

$$\sqrt{\frac{k_y}{k_x}} = 2.14$$

To align the major axis of the ellipse along the y-axis, we can without loss in generality, set $\omega_{xo} = 0$. Then

$$\left.\begin{aligned} \omega_x &= -0.467\ \omega_{yo} \sin \beta t \\ \text{and} \quad \omega_y &= \omega_{yo} \cos \beta t \end{aligned}\right\} \tag{9}$$

The maximum wobble angle is, from (9),

$$\tan \theta_m = \frac{\omega_{y\ MAX}}{\omega_z} = \frac{\omega_{yo}}{\omega_z} \tag{10}$$

Differentiating (9) gives the angular acceleration components in wobble as

$$\left.\begin{aligned} \dot{\omega}_x &= -0.467\ \beta\ \omega_{yo} \cos \beta t \\ \text{and} \quad \dot{\omega}_y &= -\beta\ \omega_{yo} \sin \beta t \end{aligned}\right\} \tag{11}$$

The maximum absolute value of angular acceleration, α, is from (11)

$$\alpha = \dot{\omega}_{y\ MAX} = \beta\ \omega_{yo}$$

or, substituting from (10)

$$\alpha = \beta\ \omega_z \tan \theta_m. \tag{12}$$

The perception threshold value of maximum wobble angle based on nystagmus blurring is found by combining (1) and (12). Thus,

$$\tan \theta_m = \frac{6.8 \times 10^{-3}}{\beta \omega_z \; (1-e^{-0.1\pi/\beta})} \tag{13}$$

where the time of disturbance duration, t, has been taken as the half period of the wobble; i.e.,

$$t = \frac{\pi}{\beta} \; .$$

Similarly, the perception threshold value of maximum wobble angle based on the Coriolis illusion is from equations (6) and (12)

$$\tan \theta_m = \frac{0.06}{\beta \; \omega_z} \tag{14}$$

RESULTS

The preception threshold wobble angles from equations (13) and (14) are plotted as a function of wobble frequency (β) and vehicle spin rate in Figure 2.* Results are also given in terms of the excess energy ratio, defined by Anderson[(2)] as the percent extra kinetic energy in the wobble state compared to the steady rotation state with minimum energy but the same angular momentum. Since a subject cannot sense angular acceleration below the threshold value and, on the other hand, can easily tolerate values of angular acceleration substantially exceeding threshold, it seems conservative to interpret the results as wobble angle limits. Note that nystagmus blurring, the involuntary, non-subjective response, yields the more stringent limit.

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*At a wobble angle of 18.5°, the error in the maximum acceleration given by the linearized theory presented here is about 5%, and this error increases as the wobble angle or excess energy ratio increases. The dotted portions of the Nystagmus and Coriolis threshold curves, given by the linear theory, correspond to angular accelerations more than 5% different from proposed threshold accelerations given by (1) and (6) respectively.

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Attachments

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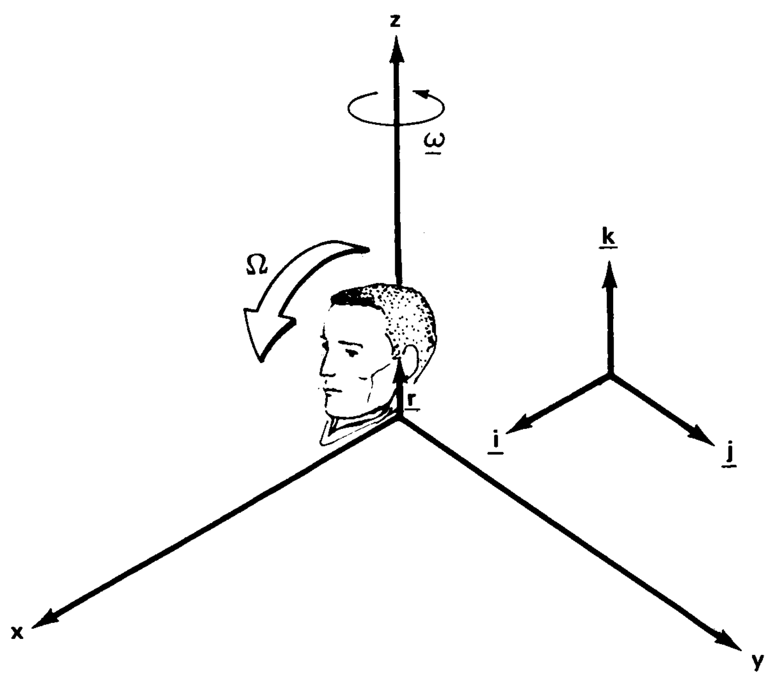

FIGURE 1 - CORIOLIS ILLUSION MECHANISM

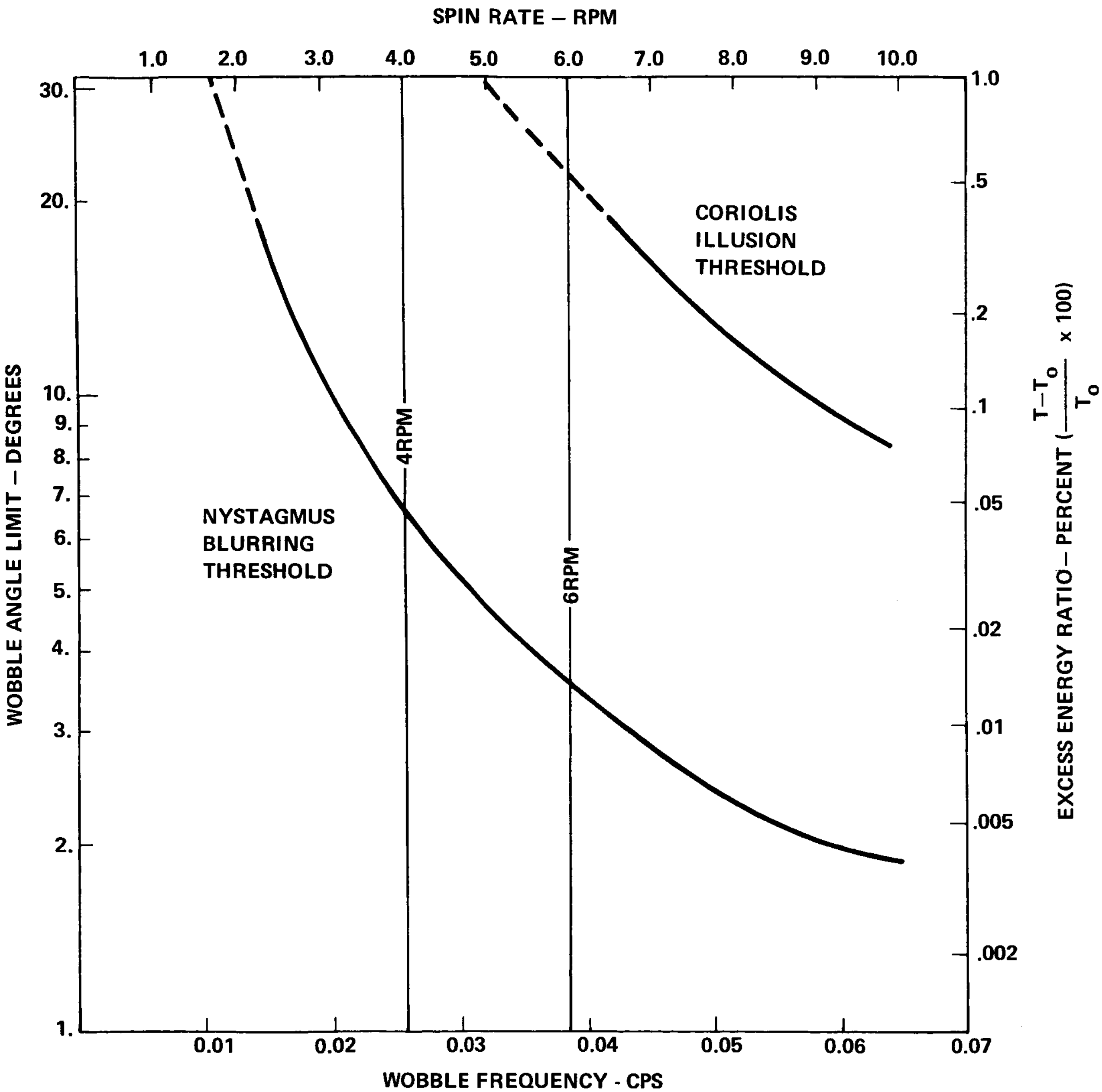

FIGURE 2 - WOBBLE ANGLE LIMIT VS. WOBBLE FREQUENCY AND SPIN RATE